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On the charged current neutrino-nucleon total cross section at high energies

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Abstract

We evaluate the charged current neutrino-nucleon total cross section up to neutrino energies of 10^{12} GeV in the LO and NLO of perturbative QCD within the framework of two different factorization schemes. The numerical implications of some inconsistent QCD calculations are illustrated.

In a recent publication [1], utilizing our latest next-to-leading order (NLO) parton distribution functions (pdfs) in the 'fixed flavor number scheme' (FFNS) [2] and 'variable flavor number scheme' (VFNS) [3], some conclusions concerning the charged current (CC) neutrino-nucleon total cross sections at high energies were drawn which deserve a closer examination. For this purpose we shall follow the standard formalism as outlined in [4] which operates within the framework of the $\overline{\mathrm{MS}}$ factorization scheme compatible with the $\overline{\mathrm{MS}}$ distributions in [2, 3].

The perturbative stability is reexamined in Fig. 1(a) which presents K_{FFNS} and K_{VFNS} where $K \equiv \sigma^{\nu N}_{\mathrm{NLO}}/\sigma^{\nu N}_{\mathrm{LO}}$. These results differ from the ones presented in Figs. 5 and 6 of [1] where the NLO pdfs were inconsistently also folded with the leading order (LO) sub-cross sections. The effects of this inconsistency are demonstrated by comparing the inconsistent results in Fig. 1(b) with the results in Fig. 1(a). These inconsistent results in Fig. 1(b) are similar to the ones in Fig. 6 of [1]. It should be furthermore noted that, contrary to the procedure in [1], our NLO FFNS predictions are *not* treated via the ACOT formula (10) in [1] but rather according to the aforementioned $\overline{\mathrm{MS}}$ prescriptions [4] which is the consistent way to regularize the NLO mass singularities within the $\overline{\mathrm{MS}}$ factorization scheme utilized in [2, 3]. Clearly, once pdfs have been extracted from experiment by employing one specific factorization scheme, they must *not* be used for calculations based on different schemes. Anyway, the difference between the results in Fig. 1(a) and the inconsistent ones in Fig. 1(b) is mainly caused by the inconsistent use of NLO pdfs for LO calculations and far less caused by the mismatch of schemes [1]. For completeness we also show in Fig. 1 the predictions based on our previous FFNS GRV98 pdfs [5], which differ very little from the ones based on our more recent FFNS GJR pdfs [2].

A comparison of the VFNS and FFNS predictions in LO and NLO is presented in Fig. 2 showing the corresponding $\sigma^{\nu N}_{\mathrm{VFNS}}/\sigma^{\nu N}_{\mathrm{FFNS}}$ ratios. (Note that the VFNS pdfs in [3] have been generated from the ones in the FFNS [2] where the full heavy quark mass dependence has been taken into account.) The VFNS expectations are similar for the

CTEQ pdfs [6] with a K-factor somewhat closer to 1 at highest energies, i.e., about 0.7 at $E_\nu = 10^{12}$ GeV instead of 0.6 for our VFNS pdfs [3] according to Fig. 1(a). The difference between the VFNS and FFNS amounts to at most about 20% at highest energies which is a typical theoretical uncertainty due to different (possible) choices of factorization schemes. It should be emphasized that the VFNS is by no means superior to the FFNS at large scales ($Q^2 \gg m^2_{c,b}$) as commonly claimed. This is due to the fact that in the VFNS the heavy quark flavors (c, b, and eventually t) also become massless partons within the nucleon with distributions obtained from massless evolutions starting at the "thresholds" $Q^2 = m^2_{c,b,t}$. Thus it is an additional *assumption*, rather than a theoretical necessity, that these massless "heavy" quark pdfs are relevant asymptotically and that they correctly describe the asymptotic behavior of deep inelastic structure functions and cross sections for large scales. In fact if perturbative stability is considered as a selective criterion, then Fig. 1(a) speaks in favor of the FFNS at very high neutrino energies, i.e. at $E_\nu \gtrsim 10^8$ GeV, where, according to Fig. 2, the NLO VFNS and FFNS predictions differ considerably.

The predicted total cross sections as calculated at NLO in the FFNS can be inferred from Fig. 3 which can be combined with Fig.1(a) and/or Fig. 2 whenever desired. We also depict in Fig. 3 the individual contributions from the CC subprocesses of the light ($W^+d \to u$, $W^+s \to u$, $W^+\bar{u} \to \bar{d}$, etc.) and heavy quarks, with the charm contribution deriving from the $W^+s \to c$ and $W^+d \to c$ transitions and the $\mathcal{O}(\alpha_s)$ contributions $W^+g \to c\bar{s}$, $W^+s' \to gc$, etc., where $s'_{\nu N} \equiv |V_{cs}|^2 s + |V_{cd}|^2(d+u)/2$, as described, for example, in [4, 7] for the $\overline{\mathrm{MS}}$ factorization scheme, with V_{ij} denoting the standard CKM matrix elements. The fact that the heavy $t\bar{b}$ FFNS contribution has so far only been calculated in LO ($W^+g \to t\bar{b}$) is of minor importance, since the $c\bar{s}$ sector dominates over the much heavier $t\bar{b}$ one. For consistency reasons we calculated this fully massive ($m_{b,t} \neq 0$) contribution always using the LO gluon distribution. This is immaterial at $E \lesssim 10^8$ GeV where the $t\bar{b}$ contribution to $\sigma^{\nu N}_{\rm tot}$ is negligible while at higher energies this amounts to an uncertainty of only a few percent due to the fact that the NLO massive $t\bar{b}$ contribution would amount to an $\mathcal{O}(\alpha_s)$ correction to the LO contribution of about 20%.

To summarize, we have demonstrated that fully consistent LO and NLO QCD calculations of CC neutrino–nucleon total cross sections within the framework of two different factorization schemes (FFNS, VFNS) yield rather stable perturbative results even at ultra-high neutrino energies of about 10^{12} GeV. The FFNS results turn out to be more stable than the VFNS ones at highest energies. The difference between the FFNS and VFNS results amounts to at most about 20% at highest energies of 10^{10} to 10^{12} GeV, which is a typical theoretical uncertainty due to different (possible) choices of factorization schemes.

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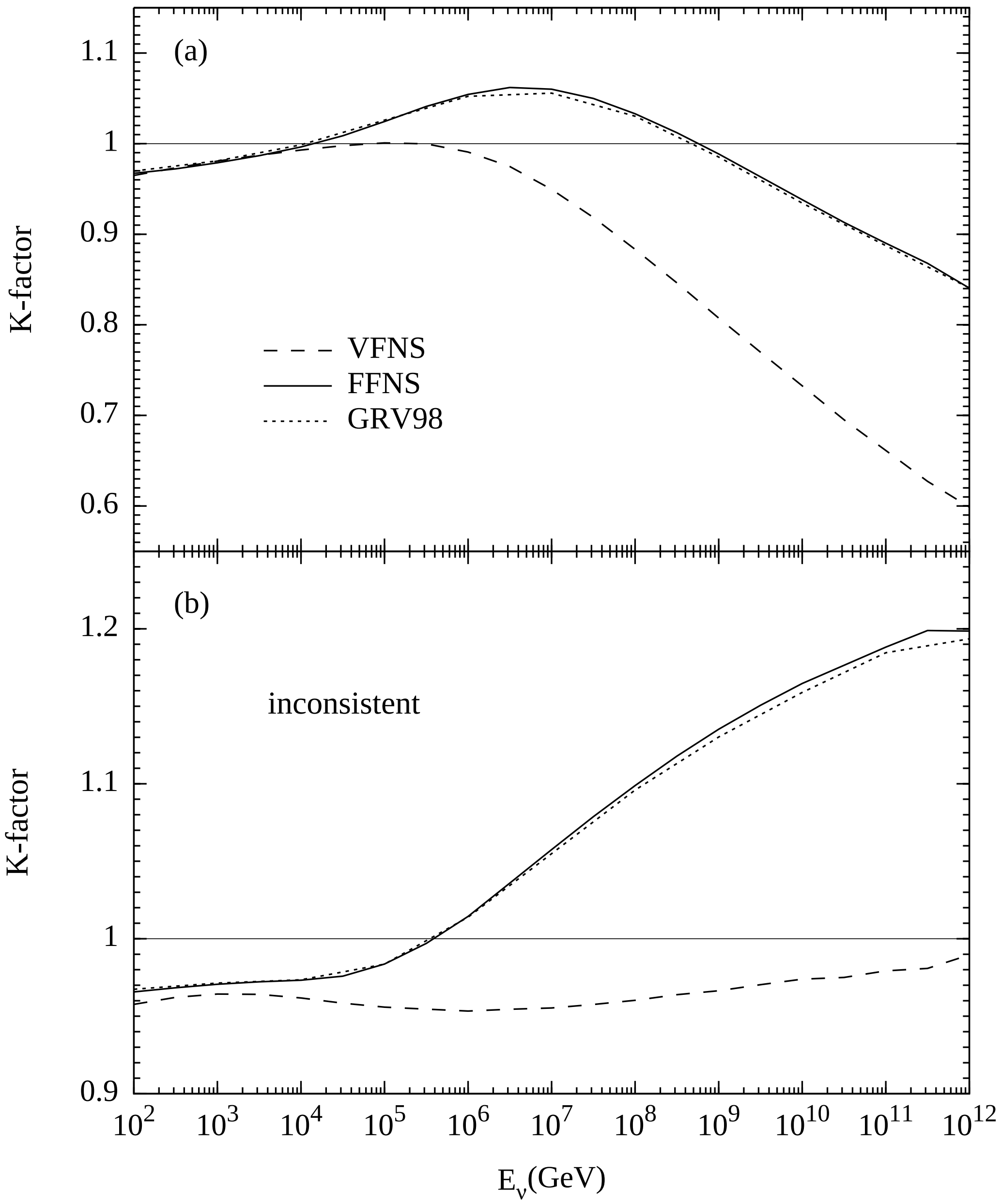

Figure 1: (a) Predictions for the $K \equiv \sigma_{\rm NLO}^{\nu N}/\sigma_{\rm LO}^{\nu N}$ factors of the CC cross sections in two different factorization schemes, using the FFNS GJR [2] and GRV98 [5] pdfs, and the VFNS pdfs of [3]. The inconsistent K-factors in (b) have been evaluated using always the same NLO pdfs also at LO as was done in [1].

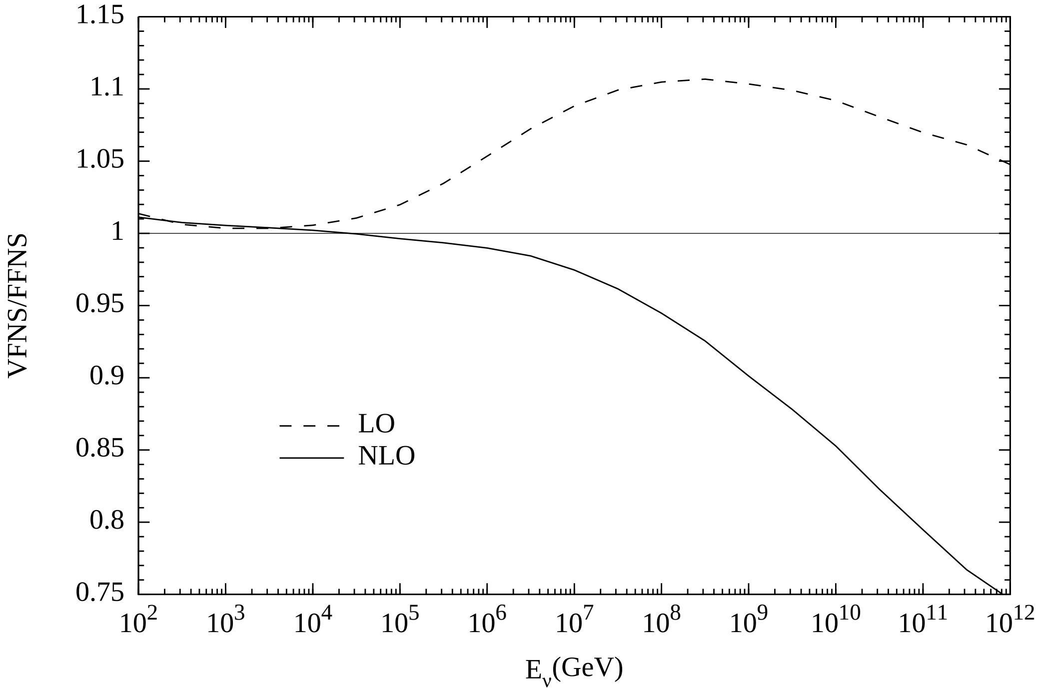

Figure 2: The ratios of CC νN cross sections as calculated in the VFNS [3] and FFNS [2] at LO and NLO. The ratios are similar if the VFNS CTEQ6 pdfs [6] are used instead.

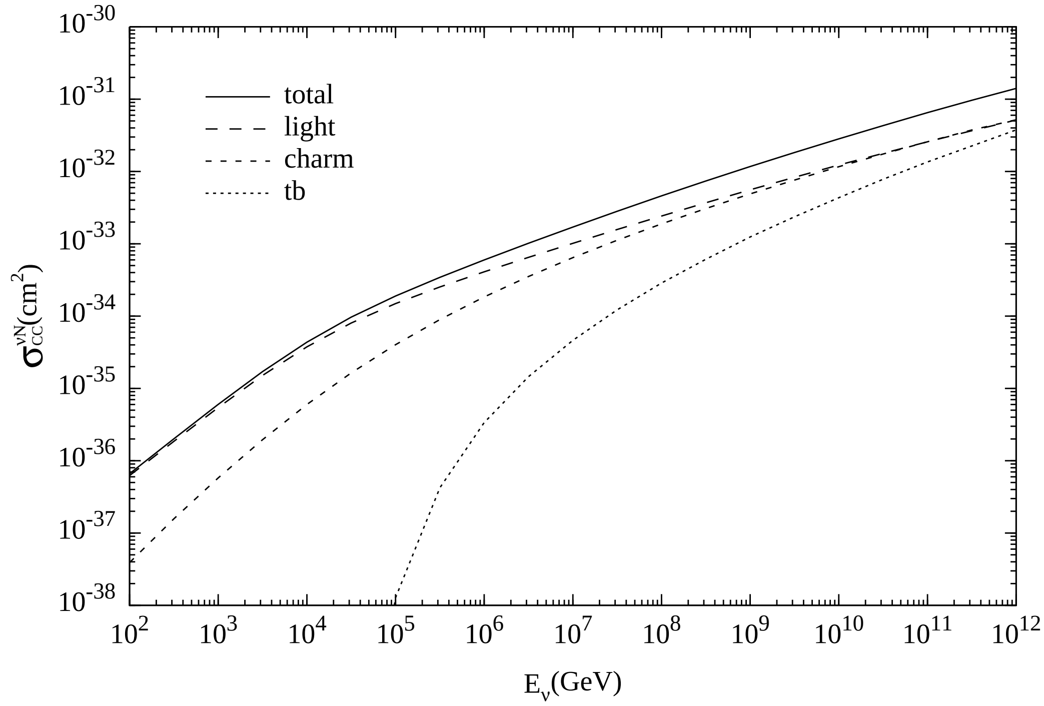

Figure 3: The total CC νN cross section as calculated at NLO in the FFNS using the GJR pdfs [2]. The individual contributions due to light ($d \to u$, $s \to u$, $\bar{u} \to \bar{d}$, etc.) and charm ($s \to c$, $d \to c$, etc.) quark CC transitions are shown as well. The fully massive tb contribution has so far been calculated only in LO according to the subprocess $W^+ g \to t\bar{b}$ which, for consistency reasons, has to be folded also with the LO gluon distribution.